

TITLE OF INVENTION

Flexible Process Optimizer

CROSS-REFERENCE TO RELATED APPLICATIONS

Not Applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable.

BACKGROUND OF THE INVENTION

1. Field of Invention

**[0001]** This invention pertains to an apparatus for monitoring and controlling a production process. More specifically, this invention pertains to an apparatus connected to a production machine that acquires and analyzes data about the production process and adjusts the production machine to improve the efficiency of the production process.

2. Description of the Related Art

**[0002]** Most industrial processes used for production of discrete components or for continuous products involve a multitude of variables that affect the final product quality as well as the production efficiency or productivity. An example of a continuous production system is a paper mill producing rolls of paper of certain composition, thickness, and other characteristics to meet customer specifications. An example of a discrete component production system is a precision grinding machine making automotive cam shafts, crankshafts, or other components. Maximizing the product quality as well as productivity in a competitive environment requires a certain degree of control of the production system. This is generally only possible with the help of real time data of key process parameters and product quality attributes acquired using sensors installed on the production equipment. Although production equipment may possess the components needed to move the slides and spindles at

numerically controlled rates or furnace controls to maintain a certain temperature, the sensors to provide the information about the system behavior are not always available and may have to be added. The availability of real time process data combined with the controllability of the production machines still requires the determination of a control strategy or methodology best suited for an effective process control under a given set of production conditions. To complicate matters further, certain conditions such as incoming stock on each part or the instantaneous sharpness of the tool may be dynamic variables and therefore are generally not known.

**[0003]** Some attempts have been made in the past towards fully automatic control of the process. However, this requires instrumenting the production machines to obtain real time information on the machine and spindle stiffness as well as the actual tool sharpness. Typical of the prior art are the devices of the following patents.

<u>Patent Number</u>	<u>Inventor</u>	<u>Issue Date</u>
4,855,925	Bhateja	Aug. 8, 1989
4,570,389	Leitch, et al.	Feb. 18, 1986
4,590,573	Hahn	May 20, 1986
6,098,452	Enomoto	Aug. 8, 2000
6,128,547	Tomoeda, et al.	Oct. 3, 2000
6,234,869	Kobayashi, et al.	May 22, 2001

**[0004]** Leitch, et al., describe an automatic adaptive system to maintain a constant wheel sharpness without wheel breakdown. Hahn describes a computer controlled technique for rounding up holes in a grinding taking into account the spindle deflection. The inventions of Enomoto and Tomoeda automatically control the final workpiece diameter using a measuring head during grinding. Kobayashi describes measuring the ground workpiece diameter using a gauge head to reveal any abrupt changes or lack of changes in part size during grinding.

**[0005]** The inventions identified above are generally directed to attempts at the automatic control of a grinding operation based upon a specific, predetermined attribute of a the workpiece. However, none of these prior art patents disclose how to

optimize and control the grinding process based upon broad criteria of workpiece quality attributes and system productivity, nor do they provide the flexibility to change the optimization criteria according to the specific process or the desires of the user. Finally, the prior art control systems require instrumented machines with sensors and gauge heads and, therefore, are generally not adaptable to existing grinding machines lacking the necessary instrumentation.

#### BRIEF SUMMARY OF THE INVENTION

**[0006]** An apparatus for recording various parameters of a production process and analyzing the information gained from the parameters to improve the efficiency of the production process is shown and described. The flexible process optimizer combines data acquisition capabilities with data analysis tools to provide a user with the ability to visualize how the machine is behaving during the production process and what areas need improvement. The flexible process optimizer acquires data from sensors mounted on a production machine and plots the sensor data on a display allowing the user to see in detail what is really happening inside the production process. The flexible process optimizer permits the user to control fully the measurement ranges, full scales, and other features of all the sensors used to monitor the process. From the qualitative sensor data display, the user can analyze the process signatures in the time domain and the frequency domain to spot inefficiencies in the production process. By identifying the inefficiencies in the production process, the process parameters can be adjusted to reduce or eliminate the inefficiency thereby directly improving the efficiency of the production operation. In addition, the user can compute specific quantitative parameters from the process data. Analyzing these specific values helps quantify the process capability for comparison with other similar systems and to insure that the process demands do not exceed the physical limitations of the production system. Having the qualitative data and the quantitative data provides a precise measure of the production system behavior and allows the performance levels of different production operations to be compared.

## BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0007] The above-mentioned features of the invention will become more clearly understood from the following detailed description of the invention read together with the drawings in which:

Figure 1 illustrates a flexible process optimizer of the present invention in a production environment;

Figure 2 is a block diagram of the flexible process optimizer;

Figure 3 is a block diagram of the main circuit of the flexible process optimizer;

Figure 4 is a block diagram of a general purpose module circuit for use with the flexible process optimizer;

Figure 5 is a block diagram of a vibration module circuit for use with the flexible process optimizer;

Figure 6 is a block diagram of a power module circuit for use with the flexible process optimizer;

Figure 7 is a flow chart of the major functions of the flexible process optimizer;

Figure 8 is a flow chart of the initialization function of the flexible process optimizer;

Figure 9 is a flow chart of the data acquisition function of the flexible process optimizer;

Figure 10 is a flow chart of the data analysis function of the flexible process optimizer;

Figure 11 is a flow chart of the module detection function of the flexible process optimizer of the present invention;

Figure 12 is a flow chart of the hardware diagnostic function of the flexible process optimizer;

Figure 13 is a flow chart of the calibration function for the dc inputs of the flexible process optimizer;

Figure 14 is a flow chart of the calibration function for the differential inputs of the flexible process optimizer;

Figure 15 is a flow chart of the calibration function for the 4-20 milliamp inputs of the flexible process optimizer; and

Figure 16 illustrates a graph of infeed, part size, and power for one cycle of a production grinding process;

Figure 17 illustrates a graph of the wheel hungriness parameter; and

Figure 18 is a flow diagram of the calibration function for an linear variable differential transformer input.

#### DETAILED DESCRIPTION OF THE INVENTION

[0008] An apparatus for recording various parameters of a production process and analyzing the information gained from the parameters to improve the efficiency of the production process, or flexible process optimizer **100**, is shown in the accompanying figures and described herein. The flexible process optimizer **100** combines data acquisition capabilities with data analysis tools to provide a user with the ability to visualize how the machine is behaving during the production process and what areas can be improved.

[0009] Figure 1 illustrates the environment of the flexible process optimizer **100** of the present invention. The flexible process optimizer **100** includes two main components: an interface module **102** and a processing device running the system and application software **104**. In the illustrated embodiment, the flexible process optimizer **100** is shown with the interface module **102** attached to a personal computer running the system software; however, those skilled in the art will recognize that the interface module and the processing device can be integrated into a single unit. The flexible process optimizer **100** acquires data from sensors mounted on a production machine **106** and plots the sensor data on a display, thereby allowing the user to see in detail what is happening inside the production process. The flexible process optimizer **100** permits the user to control fully the ranges, full scales, and other features of all the sensors used to monitor the process. In the illustrated embodiment, the production machine **106** is a grinding machine with a grinding wheel **108** adapted to engage and disengage a workpiece **110**. The grinding wheel **108** generally moves into and out of the workpiece **110** along a line parallel to line **112**. The workpiece **110** is generally moved along a line parallel to line **114** in relation to the grinding wheel **108**. From the qualitative sensor data display, the user

can analyze the process signatures to spot inefficiencies in the production process. By identifying the inefficiencies in the production process, the process variables can be adjusted to reduce or eliminate the inefficiency thereby directly improving the quality and productivity of the production operation. In addition, the user can compute specific quantitative values from the process data. Analyzing the specific parameter values helps quantify the process capability and the physical limitations of the production system. Having the qualitative data and the quantitative data provides a precise measure of the production system behavior and allows the performance levels of different production operations to be compared. Using this information, a balanced control strategy can be developed and implemented.

[0010] Figure 2 illustrates a block diagram of the flexible process optimizer **100** of the present invention. The flexible process optimizer **100** accepts a number of module circuits **202** that monitor various parameters through transducers or probes attached to a target machine **216**. The outputs of the module circuits **202** are conditioned by an appropriate signal conditioning circuit **204**. A processor interface **206** connects the flexible process optimizer **100** to a processing device **208**, such as an external personal computer. In one embodiment, the processor interface **206** includes an interface port known to those skilled in the art, including but not limited to PCMCIA, PCI, serial, parallel, IEEE 1394, and USB. Connected to the processing device are a display device **210** and a storage device **212**. The display device **210** is used to display either or both of the raw data and the processed data. The display device **210** also provides the user interface to permit the entry of user specific information for the production system, the desired sensor range, desired display, the desired process control limits, and other setup information. The storage device **212** saves either or both of the raw data and the processed data. Finally, the machine interface **214** communicates directly with the controller of the target machine **216**. The machine interface **214**, the flexible process optimizer **100** reads the current controller settings. The setting information is combined with the values measured during the process cycle to allow the user to see how the process responds to the controller settings. Through the flexible process optimizer **100**, the user adjusts the controller settings to optimize the process and the machine interface **214** adjusts the settings of the controller in the target machine **216**. Those skilled in the art will

recognize that the processing device can be integrated into the flexible process optimizer without departing from the scope and spirit of the present invention.

[0011] Figure 3 illustrates one embodiment of the main circuit **300** of the flexible process optimizer in greater detail. The main circuit **300** includes a power supply **302**. In one embodiment, the power supply **302** is a universal input (90 to 260 volts) switch mode power supply providing +3.3, +5, +12, -12, +15, and -15 volt dc outputs. The 3.3 and the 5-volt outputs are generally used to power digital circuits while the 12 and 15 volt outputs are generally used to power analog circuits. Those skilled in the art will recognize that other voltages can be supplied by the power supply **302** as necessary. A digital interface circuit **304** on the main circuit **300** interfaces an analog-to-digital converter (ADC) card of a personal computer and the flexible process optimizer **100**. The special codes that are generated by the flexible process optimizer software are decoded in this circuit. The internal buses are also generated by the digital interface circuit **304**. The main circuit **300** also includes a number of module slots **306** in which various module circuits can be plugged to customize the flexible process optimizer **100**. The set of modules plugged into the module slots **306** determines the configuration of the flexible process optimizer **100** and, in association with the system software, fixes the application of the flexible process optimizer **100**.

[0012] The main circuit **300** has several controls for adjusting various parameters of the attached modules. A gain control circuit **308** generates the control signals required by the individual modules for applying a gain to the input signal. The gain control circuit **308** can include a multiple-stage gain control to allow both coarse and fine control of the gain or one or more single-stage gain controls accomplishing the same effect. An offset control circuit **310** generates the control signals required by the individual modules for applying an offset to the input signal. The offset control circuit **310** can include a multiple-stage offset control to allow both coarse and fine control of the offset or one or more single-stage offset controls accomplishing the same effect. The main circuit further includes a module latch control circuit **312** that generates the control signals required for latching the mode, filter, LVDT excitation, coarse gain information in the individual modules. It will be understood by those

skilled in the art that the various controls can be replicated to provide the required number of unique controls. Replication allows for individual control over separate modules, for example gain and offset, or the generation of multiple unique signals for a single module, for example multiple latch controls.

[0013] A digital-to-analog converter (DAC) circuit **314** generates a diagnostic voltage for the attached modules with the desired resolution. The DAC **314** generates an appropriate diagnostic voltage, which can be adjusted with the precision of the number of available millivolt steps under control of the system software. The diagnostic voltage is also used for calibrating the different sensors under control of the system software. A standard +5 or +10-volt reference **316** is included for calibrating the module circuits and the various sensors under control of the system software. A light-emitting diode (LED) driver circuit **318** illuminates a plurality of LEDs that indicate the presence and/or status of the various modules present in the flexible process optimizer **100**.

[0014] Figure 4 illustrates one embodiment of a general purpose module circuit **400** adapted to accept inputs from a sensor **406**, such as a linear variable differential transformer (LVDT), a 4 to 20 milliamp current loop, a dc voltage sensor, or a differential voltage sensor for use in the flexible process optimizer **100** of the present invention. The input type is selected from the system software. In order to directly accept inputs from a variety of ac type LVDTs, a LVDT excitation and demodulation circuit **402** is built in the module **400**. The LVDT excitation and demodulation circuit **402** generates the necessary ac excitation voltage and frequency for the LVDT primary. The excitation voltage and frequency are varied under the control of the system software. The LVDT excitation and demodulation circuit **402** also produces a dc voltage corresponding to the LVDT displacement. Other inputs are accepted from an input conditioning circuit **404** that converts 4 to 20 milliamp and differential voltage signals to a dc voltage. The input conditioning circuit **404** includes a preamplifier stage to avoid any loading on the output of sensors. Those skilled in the art will recognize that module can be modified to accept less than all of the inputs described without departing from the scope and spirit of the present invention. For example, the module can be configured without the LVDT excitation circuit and

corresponding input circuitry or, alternatively, the module can be configured without the input circuitry for accepting a differential input or the input from a current loop.

[0015] The module **400** transfers signals to and from the flexible process optimizer **200** through a module connector **426** adapted to be received within a module slot **300**. A first latch **408** holds the value of the LVDT excitation voltage and the types of input selected like DC, differential etc. A second latch **410** holds the filter value. It holds one of the possible values of the filter. Those skilled in the art will recognize other devices such as a memory can be used for holding the filter or other values without departing from the scope and spirit of the present invention. A switching circuit **412** selects one of the inputs like dc, LVDT, +5V reference voltage, etc., under the control of the system software. The switching circuit **412** also contains an analog switch that provides a pass-through feature, which passes the input signal to the adjacent module hardware via the main circuit **300**. This feature allows any connected input to be calibrated to two different ranges through the hardware of two adjacent modules and the input data can be acquired, viewed, and saved on two separate channels. A hardware amplifier and filter **414** is implemented using a low-pass analog or digital filter circuit applied to the sensor output. There are a number of different time constants that can be selected under control of the system software. A DAC coarse offset control circuit **416** generates a coarse offset voltage under control of the system software. In one embodiment, the maximum offset voltage is approximately 10 volts in steps of a few millivolts. A DAC fine offset control circuit **418** generates a fine offset voltage under control of the system software. In one embodiment, the maximum offset voltage of a few millivolts in fractional millivolt steps. A two-stage coarse gain amplifier **420** under control of the system software. In one embodiment, the two-stage coarse gain amplifier **420** is implemented using a special low noise amplifier and offers precision gain steps in the range of 1 to about 10,000. A third latch **422** holds the coarse gain value under control of the system software. A fine gain amplifier **424** amplifies the input with a gain in the range of about unity to about 10. The gain range of the fine gain amplifier **424** is divided into a number of steps, for example offering up to 10,000 gain increments between 0 and 10 and is selected through the system software.

[0016] Figure 5 is a block diagram of a vibration module circuit **500** for use in the flexible process optimizer **100** of the present invention. In one embodiment, up to four piezoelectric vibration sensors **518** can be connected to the vibration module circuit **500**. No external power source for the sensors **518** is required as power for the sensors is supplied from the base current through the module circuit **500**. The vibration module circuit **500** transfers signals to and from the flexible process optimizer **100** through a module connector **520** adapted to be received within a module slot **306**. A piezoelectric vibration sensor **518** requires a constant current power supply **502**. A multiple-stage coarse gain circuit **504**, which in the illustrated embodiment is a two-stage circuit, is provided for each vibration sensor input. The system software controls the gain of each multiple-stage coarse gain circuit **504** in steps in the range of 1 to about 1,000. For the first and second vibration sensor inputs, a first coarse latch circuit **506** holds the gain value of coarse gain amplifiers. A filter latch **508** holds the filter step of the associated hardware amplifier and filter **510**. Each hardware amplifier and filter **510** is a low pass filter circuit with one of a number different time constants that are controlled through the system software. The low pass filter is applied to the sensor signal after amplifier through the multiple-stage coarse gain circuit **504**. The third and fourth vibration sensor inputs are handled either simultaneously or independently, as shown in Figure 5. A second coarse latch **512** holds the gain value of the coarse gain amplifiers **504** associated with the third and fourth vibration sensors. There is no hardware filter associated with the third and fourth vibration sensor inputs in the illustrated embodiment; however those skilled in the art will recognize that any or all of the sensor inputs can include analog or digital filters without departing from the scope and spirit of the present invention.

[0017] A switching latch **514**, under the control of the system software, holds the status of a switching circuit **516** such as the module and connector identifier, the diagnostic voltage, etc., thereby controlling the output of the switching circuit **516**. The switching circuit **516** switches to the signal based on the value stored in the switching latch **514**. The switching circuit **516** sends selected signal to the analog and digital outputs of the module.

**[0018]** Figure 6 is a block diagram of a power module circuit **600** for use in the flexible process optimizer **100** of the present invention. The power module circuit **600** transfers signals to and from the flexible process optimizer **100** through a module connector **618** adapted to be received within a module slot **306**. A sensor range detection and range setting circuit **602** interfaces with a power sensor **616**, such as that produced by Monitech Systems, Inc., to read the range of the power sensor **616**. Controlled by the system software, the sensor range detection and range setting circuit **602** provides the ability to change the range of the power sensor **616**. The power module circuit **600** also includes a sensor latch **604**, which is under the control of the system software, that holds the range value of the power sensor **616**. A switching latch **606** holds the commands from the system software to select the module identifier, the diagnostic voltage, the reference voltage, etc. A switching circuit **608** switches to the signal based on the value stored in switching latch **606** and sends the module identifier, the diagnostic voltage, or the reference voltage to the analog output of the power module circuit **600**. A filter latch **610**, which is controlled by the system software, holds the step value of hardware filter. A hardware filter and amplifier **612** is a low pass filter circuit with one of a number of different time constants controlled through the system software. The low pass filter is applied to the sensor signal after the amplifier output. A buffer amplifier **614** buffers the signal at the output stage.

**[0019]** Those skilled in the art will recognize that the number of values available, the number of stages available, the size of the steps, the ranges of adjustment, and the maximum values can be varied based upon the hardware components and the specifications of the various module circuits can vary without departing from the scope and spirit of the present invention.

**[0020]** The flexible process optimizer **100** allows the users of existing machines without built in sensors to obtain key data and observe patterns that allow the user to gain control of the operation without making major alterations to the machines in the production environment. The flexible process optimizer **100** provides a balanced and easy-to-use control strategy and empowers the user to tailor the control to the user's specific need in any particular production operation. A balanced control strategy is

defined in terms of controlling multiple output parameters of specific interest to a user.

**[0021]** One application of the flexible process optimizer **100** is monitoring and controlling a precision production grinding machine. A typical production grinding operation consists of feeding the rotating grinding wheel into a rotating workpiece (or vice versa) by means of a slide carrying the moving member. Material is removed from the workpiece at a certain rate during the interaction of the workpiece and the grinding wheel until the workpiece diameter reaches a desired size and surface finish. The infeed of the movable member, say the grinding wheel, is controlled carefully at various feed rates during the production cycle to provide the grinding pressures to remove the desired material as well as to finish the work piece surface in an acceptable cycle time. The feed rates are dependent upon the capabilities of the machine and the grinding wheel in use. In one embodiment, the flexible process optimizer **100** takes the sensor signals, performs the needed signal conditioning, and displays the data on a visual display. The user analyzes the visual display and makes manual control adjustments to the operation of the production grinding machine. In another embodiment, more sensors, data analysis features, and control lines are interfaced with the hardware of the production grinding system and its CNC control to allow control of the production process. The desired process control is effected by changing the machine feed rates and the change points along with the wheel dressing conditions and wheel dressing frequency. During this process the finished ground part quality data such as actual final size, taper, and, roundness are stored for quality inspection and reporting purposes.

**[0022]** In production grinding, examples of the quantitative parameters may include the grinding wheel hungriness; that is its ability to remove material from a workpiece. Hungriness is usually not measured and yet it is a major cause of inefficiency and lack of control in production grinding operations. By nature, the key process parameters required for an effective process control depend upon the industrial process being monitored. In addition to the discrete component grinding and machining industry, continuous processes in industries such as: paper and pulp processing, food processing, pharmaceutical processing, and paints and chemical

processing have a large number of special parameters such as: mixture consistency, temperatures, humidity, etc., which determine the product quality as well as the system productivity.

[0023] Using precision grinding to illustrate the present invention, there are typically three sensors used for monitoring the machine. These include a power sensor to measure grinding wheel power consumption, an infeed sensor to measure the grinding wheel (or workpiece) slide, and a gauge head sensor to measure the instantaneous diameter of the work piece during the actual grinding operation. The grinding wheel power consumption is considered a process output, the infeed is considered a process input, and the diameter is considered a product quality attribute, which is indicative of the system output. With these three measurements recorded and displayed by the flexible process optimizer **100**, the user has sufficient information to determine the best optimization strategy and make the necessary adjustments to the grinding machine to improve the efficiency of practically any grinding process.

[0024] For a balanced optimization and control of the process in a production grinding system, other parameters of interest include a ground component end-to-end taper, the total grinding cycle time, and other features of certain process parameters during a particular phase of the grinding cycle. One such feature is the grinding power. Whether the grinding power is kept high or low and is maintained at a certain level for a certain duration during the grinding operation affects the final component size (within the resolution capability of the inprocess size control gauge) and the component surface roughness, roundness, and taper. The need for a user definable flexible process optimizer arises from the fact that the ground product quality on a given production machine varies with the condition of the grinding wheel and the equipment as well as incoming part quality and these also significantly affect the production cycle times.

[0025] In an advanced application of the flexible process optimizer to a precision production grinding machine, multiple sensors are used. The basic sensors include pulse encoders or LVDT probes for monitoring machine slide movements, speed

sensors to track the grinding wheel and workpiece rotational speed, power sensors for measuring the wattage consumption of the wheel, the workpiece, or a rotary wheel dressing device, and a part size and geometry (taper or roundness) sensor. However, still more sensors may be used for monitoring the operation of the machine such as sensors to measure coolant flow rate, pressure, or temperature, etc. The flexible process optimizer **100** of the present invention is adaptable, through replaceable module circuits, to measure most any variable that causes or detects process variability. In addition to monitoring the process data, the flexible process optimizer **100** can also measure the vibration at selected locations of the machine during the actual grinding operation. Such information generally relates with the condition of machine spindles and other structural pieces which can cause poor product quality deterioration and is taken at faster data rates than the typical slow process data designed to capture process changes which are much slower.

**[0026]** Figure 7 illustrates a flow chart of the major functions of the flexible process optimizer **100**, which are controlled through the processing device running the system software. The first major function is the initialization of the flexible process optimizer **700**, which includes the auto-detection of installed module circuits **702** and the automatic configuration and calibration of installed module circuits **704**. The second major function is the acquisition of data **710**, which includes reading the sensors attached to a production machine **712** and conditioning the input signals **714**. The third major function is the evaluation of the acquired data **720**, which includes displaying the process data **722** and the evaluation of process efficiency based upon the conditioned process data **724**. The last major function is the generation of control signals to adjust parameters of the production machine to improve the efficiency of the production process **730**, which includes the generation of control signals for adjusting the machine process **732** and the reconfiguration of the production machine using the control signals **734**.

**[0027]** Figure 8 charts the flow of the initialization function **700** in greater detail. First, the system software queries the flexible process optimizer **100** to identify the installed module circuits **800**. The system software automatically performs diagnostic testing **802** on the main circuit and the installed module circuits to verify

proper operation of the hardware. If the main circuit or any of the installed module circuits fail testing **804**, the user is notified of the failure **806**. Next, most of the properly functioning module circuits are automatically calibrated by the system software **808**.

**[0028]** Figure 9 charts the flow of the data acquisition function **710** in greater detail. The system software activates the various sensors **900**. From the production machine, the various sensors collect signals **902** related to the production process. The data acquisition process is monitored to identify a problem in data acquisition, such as a malfunction in the controller, the monitor unit, or the module circuits, or the disconnection of a sensor **904**. If a data acquisition interruption occurs, the user is notified **906**. The acquired data is conditioned for analysis **908**. Finally, the conditioned data is stored for analysis **910**. Those skilled in the art will recognize that the analysis may occur in real-time and rely solely on temporary storage or the data may be stored for later analysis or historic purposes in a non-volatile storage medium. Under control of the system software, the flexible process optimizer **100** is capable of running unattended with scheduled data storage intervals. The storage of data can also be triggered by the occurrence of certain events as configured by the user.

**[0029]** Figure 10 charts the flow of the data analysis function **720** in greater detail. The acquired and conditioned data is visually displayed for evaluation by a user **1000**. From the visual display, the user can evaluate the production process and make adjustments to the production process manually or verify that the production process is running efficiently under control of the flexible process optimizer **100**. The user is provided with control over the presentation of the data **1002**. Some of the various parameters that are under the user's control include the scale and the time base of the display window. An offset can be applied to any data input to position the data input at a desired location in the data display window. The polarity of any sensor input can be inverted by the system software for easier display and more meaningful analysis. The system software also provides the ability to filter electronic noise by applying a variable filter applied to a noisy input or to noisy saved data. The system software also allows a user to view data from the same sensor at multiple scales and time bases simultaneously for improved evaluation of the process data. The system

software also allows the user to connect a sensor to a single module slot **306** and view the same sensor data through two adjacent modules. Because the gain and offset of the modules are individually controlled, the same sensor data can be viewed with two different gains and/or offsets. The on-screen position of the process data is variable by an automatic offset removal function provided through the system software. Finally, the signal conditioning electronics of the flexible process optimizer **100** are responsive to the system software to allow sensor calibration for a wider range and actual operation at a smaller range. Using this technique data may seem off-scale while being acquired; however, saved data is repositionable when recalled. This enables the flexible process optimizer to capture data at high resolution in a much wider effective range over a long period of time for unattended process monitoring of production systems. Using data analysis tools, inefficiencies in the production process are identified **1004**. The process data is analyzed using various data analysis techniques known to those skilled in the art, including statistical analysis, heuristic data analysis, pattern matching, and the application of specific algorithms.

**[0030]** Figure 11 charts the flow of the module detection function **800** in greater detail. The module detection function **800** initializes the hardware by setting the coarse gain and the fine gain to unity **1100** and by setting the coarse offset and the fine offset to zero **1102**. Next, the module detection function **800** disables the hardware filters to allow the raw input to be read **1104**. The module detection function **800** reads the module identification voltage from the module **1106**. The module identification voltage is a voltage specific to a particular module. Identification of the module is completed by looking up the module identification voltage read from the module in a look-up table **1108**. The module detection function **800** is repeated until all attached modules are identified. Those skilled in the art will recognize other structures and methods for providing an identifier to the various module circuits and using that identifier to determine which interchangeable module circuits are attached to the flexible process optimizer **100**.

**[0031]** Figure 12 charts the flow of the hardware diagnostic function **802** in greater detail. The hardware diagnostic function **802** initializes the hardware by setting the coarse gain and the fine gain to unity **1200** and by setting the coarse offset

and the fine offset to zero **1202**. Next, the hardware diagnostic function **802** disables the hardware filters to allow the raw input to be read **1204**. The hardware diagnostic function **802** reads a reference voltage from the module **1206**. The fixed reference voltage is the base input voltage for the module. This reference voltage reading varies based upon the tolerances of the components making up the module circuit. The reference voltage is compared to the ideal voltage, which would be read from an ideal module circuit. In general, the reference voltage is close to the ideal voltage so the hardware diagnostic function **802** adjusts the fine gain until the reference voltage equals the ideal voltage **1208**. If the fine gain control can be adjusted so that the reference voltage equals the ideal voltage **1210**, the hardware is considered to have passed the diagnostic check and the value of the fine gain is stored as the unity gain factor **1212**. Otherwise, the user is notified of the hardware diagnostic failure **1214** and other appropriate actions can be taken, such as terminating the monitoring process. The hardware diagnostic function **802** is repeated to verify the proper operation of each attached module.

[0032] Figure 13 charts the flow of the dc input calibration function **1300**, which is a sub-function of the calibration function **808** in greater detail. The dc input calibration function **1300** initializes the hardware by setting the coarse gain and the fine gain to unity **1302** and by setting the coarse offset and the fine offset to zero **1304**. The dc input calibration function **1300** reads a reference voltage from the module **1306**. The reference voltage is compared to a known voltage range, which represents the input range of the dc input **1308**. If the reference voltage is within the known voltage range **1310**, the hardware is considered to be properly calibrated. Otherwise, the user is notified of the hardware calibration failure **1312** and other appropriate actions can be taken, such as terminating the monitoring process. The dc input calibration function **1300** is repeated to verify the calibration of each attached module using dc inputs.

[0033] Figure 14 charts the flow of the differential input calibration function **1400**, which is a sub-function of the calibration function **808** in greater detail. The differential input calibration function **1400** reads the minimum sensor voltage from the configuration file **1402**. The main circuit generates the minimum

sensor voltage **1404** and the differential input calibration function **1400** adjusts the coarse offset and the fine offset to null the minimum sensor voltage **1406**. With the minimum sensor voltage **1406** nulled, the differential input calibration function **1400** calculates the differential voltage **1408** and the differential voltage is generated by the main circuit **1410**. The module circuit gain is then adjusted until the differential voltage is equal to a known reference voltage **1412**. If the gain control can be adjusted so that the differential voltage equals the reference voltage **1414**, the hardware is considered to be properly calibrated. Otherwise, the user is notified of the hardware calibration failure **1416** and other appropriate actions can be taken, such as terminating the monitoring process. The differential input calibration function **1400** is repeated to verify the proper operation of each attached module using differential inputs.

**[0034]** Figure 15 charts the flow of the 4-20 milliamp current input calibration function **1500**, which is a sub-function of the calibration function **808** in greater detail. The 4-20 milliamp current input calibration function **1500** reads an input current and converts the input current into a voltage **1502** and an offset equivalent to the minimum sensor voltage is applied to null it **1504**. Next, the 4-20 milliamp current input calibration function **1500** calculates the difference **1506** between the offset and the voltage and a differential voltage is generated by the main circuit **1508**. The module circuit gain is then adjusted until the differential voltage is equal to a known reference voltage **1510**. If the gain control can be adjusted so that the differential voltage equals the reference voltage **1512**, the hardware is considered to be properly calibrated. Otherwise, the user is notified of the hardware calibration failure **1514** and other appropriate actions can be taken, such as terminating the monitoring process. The 4-20 milliamp current input calibration function **1500** is repeated to verify the proper operation of each attached module using 4-20 milliamp current inputs.

**[0035]** Of all the inputs, the LVDT input is the most difficult to configure. The system software of the flexible process optimizer **100** greatly simplifies the LVDT configuration and calibration. Figure 18 charts the flow of the LVDT input calibration function. First, the calibration routine is initialized. This involves user entry scale

information including the maximum scale, which is the maximum value of the LVDT travel in units of length, and the calibrated full scale, which is the maximum value of the LVDT travel in units of voltage **1800**. The flexible process optimizer **100** then sets the gain to unity and the offset to zero **1802**. A prompt from the flexible process optimizer **100** requires the user to move the LVDT through the entire range of travel of the plunger **1804**. The system software records the minimum voltage and the maximum voltage produced by the LVDT and quickly analyzes the voltage data to identify the linear region of the LVDT **1806**. Another prompt from the flexible process optimizer **100** requires the user to position the resting point of the LDVT within the linear region **1808**. With the LDVT operating within the linear region, the offset and the gain are optimized for the LDVT input **1810**. This involves adjusting the offset so the value of the LDVT output appears to be zero at the resting point. The gain is adjusted so that the LDVT output is a known reference value when the LDVT is moved to the maximum travel extent. If the gain control can be adjusted so that the LDVT output voltage equals the reference voltage **1812** at the maximum travel extent, the LDVT hardware is considered to be properly calibrated. Otherwise, the user is notified of the hardware calibration failure **1814** and other appropriate actions can be taken, such as terminating the monitoring process.

**[0036]** The flexible process optimizer **100** provides the user the ability to observe the results of a particular production process setup. From the output of the flexible process optimizer **100**, the user can determine the changes necessary to improve the efficiency of the production process. The user then makes the changes to certain specific machine, gage and system control settings through the controller of the production machine. The flexible process optimizer **100** allows the user to immediately verify that the changes produced the desired result. The best process improvement strategy is determined by the user based upon the process sensor data and the product quality data available through the flexible process optimizer **100**, which the user selects based upon criteria of importance to the user for the specific production process being monitored. Referring again to the example of a grinding system, such conditions may include the sharpness of a grinding wheel, incoming stock amount variations on the component, and any weaknesses in the machine components due to wear. These conditions are not easily accounted for in

conventional control systems; however, through the flexible process optimizer **100** of the present invention, the user is provided the ability to both see and deal with these and other conditions.

**[0037]** One example of process improvement or optimization in a production grinding system for precision component manufacturing is discussed in some detail. However, those skilled in the art will recognize that the flexible process optimizer **100** allows a similar approach to be applied to any discrete component manufacturing or continuous process industry operation. Referring to the grinding process cycle data of Figure 16 shows the wheel-workpiece infeed **1600** having four feed rates **FR1**, **FR2**, **FR3**, **FR4** for a grinding wheel feeding into a part being ground. The change points **B**, **C**, **D**, **E**, **F**, **G** represent the times within the production cycle at which the feed rate is adjusted. The total infeed travel distance is the difference between the grinding wheel position when contact is first made with the workpiece **B** and the grinding wheel position at the beginning of the spark-out period **F**. To one skilled in the art, the production cycle can be visualized by looking at the infeed curve **1600**. The movement between change points **A** and **B** represents the rapid approach feed rate, before actual grinding takes place. The first feed rate **FR1** (change points **B** to **C**) represents the rough (fast) grinding feed rate. The second feed rate **FR2** (change points **C** to **D**) represents the medium grinding feed rate. The third feed rate **FR3** (change points **D** to **E**) represents the fine grinding feed rate. The fourth feed rate **FR4** (change points **E** to **F**) represents the finish grinding feed rate. There is no further infeed during the spark-out period between change points **F** and **G**. Retraction of the grinding wheel occurs between change points **G** and **H**.

**[0038]** On the time axis, the time between start of the infeed **A** and the end of the wheel retraction **H** represents the total duration of the active grinding cycle when the wheel and workpiece are programmed to engage with each other. The total duration does not include other components of a complete production cycle such as part unload and load, any indexing of wheel or workpiece required to position them correctly for grinding, wheel dressing in production or other similar operation when the wheel is not actually in contact with the part, or waiting for the completion of other operations. Setting the machine and controlling the operation typically involves

setting the feed rates **FR<sub>1</sub>**, **FR<sub>2</sub>**, **FR<sub>3</sub>**, **FR<sub>4</sub>** and all the change points **B**, **C**, **D**, **E**, **F**, **G** from the rapid advance of wheel to its retraction after grinding has taken place.

Figure 16 also shows the power consumption of the grinding wheel spindle **1602**, which is obtained from a power sensor, and the instantaneous size of the workpiece **1604** during these various grinding feed rates, which is obtained from a an in-process gage head positioned on the workpiece during the grinding cycle.

**[0039]** The flexible process optimizer **100** displays a continuous stream of grinding cycles as successive components are ground in production allowing the user to see not only the features of any single grinding cycle but also spot any cycle-to-cycle variations in the important features such as feed rates or change points, the power levels at different feed rates, and the pattern of the size generation curve from the in-process gage data. The flexible process optimizer **100** thus gives the user the ability to monitor multiple production process parameters and to make changes to optimize the cycle pattern and the consistency of the cycle pattern from workpiece to workpiece.

**[0040]** The system software offers many functions and features which allow a user the flexibility need to analyze and optimize a production process. These features generally relate to the configurability and usability of the flexible process optimizer **100**, which allows the user to focus on analyzing the process, and to the capabilities that enhance the performance and value of the flexible process optimizer **100** to the user. Such features include the ability to compute values for certain parameters during live data acquisition or reviewing previously saved data, providing the user with useful information not generally available when attempting to improve a process.

**[0041]** One feature is an user selectable pause during data acquisition. The inclusion of a pause during data acquisition conserves memory, reduces data file sizes, and provides the user with flexibility during the acquisition operation. The occurrence and duration of a data acquisition pause is visible to the user on any data screen window during both live data acquisition and recall. Multiple data acquisition pauses are possible on any data screen.

**[0042]** The data display screens used to visually analyze the production process

are designed to present a panoramic view of the data. When used with a long time base, the extended viewing area allows the user to view data for both the current and previous process cycles for ready comparison.

**[0043]** The data screens grant the user virtually unlimited control of the visual display. The user is free to change the input data scales, hide data for any input, change the color of the data plot lines in the data window, apply offsets of user selected amounts to position any input data anywhere on the data screen, invert any input data, and apply filters to eliminate unwanted frequencies or harmonics in the data being viewed.

**[0044]** The system software allows the user to obtain the instantaneous value of certain useful parameters at any point during the data acquisition process. Some of the available instantaneous values include the slope of the data, the average value of the data, the "area" under the curve over a certain time period, and the maximum or minimum values of the data, and the relative value of the data in relation to an user-defined reference. All instantaneous values are tabulated with time and can be saved, if desired. In addition, the system software can automatically compute the instantaneous values at user selected intervals.

**[0045]** The system software offers the user the ability to create an overlay from data obtained during the current data acquisition or from previously saved data. The data used to create the overlay can be unadjusted, expanded, or compressed as desired by the user. A saved overlay can be used as a background during data acquisition or superimposed on recalled data for comparison and qualitative analysis purpose. The visual presentation of the overlay is adjustable giving the user the flexibility to change the data plot colors, apply offsets to reposition the data and change the full scale range of the data in the overlay.

**[0046]** Recognizing the importance of documentation in any monitored process, the system software has the ability to capture any screen of data during data acquisition and data recall. In each case, the user can adjust the visual presentation of data, capture the screen image, and store the screen image in common graphical file formats such as JPEG or TIFF.

**[0047]** During process monitoring, large amounts of data are commonly acquired. However, not all of the data is useful in evaluating the process efficiency. The system software offers the user the flexibility to save only the portion of the data acquired that is of interest instead of forcing the storage of all acquired data. Each data screen is identified by a unique screen number and the user can enter the range of screen numbers to be saved. Alternatively, the user can bring up cursors on any acquired data screens to identify the specific data to be saved

**[0048]** The system software includes the capability to track gradual shifts (i.e., drift) in data resulting from slowly changing conditions such as tool wear and thermal expansion or contraction of machine members over time. Similarly, the system software is capable of detecting abrupt changes in the scale and/or the offset of the data, which is useful for identifying instantaneous events such as intentional size compensation steps or random machine slide mispositioning because of stick-slip. The accumulated total of such offsets due to gradual or abrupt discrete step changes over an user-defined period is readily available to the user for review.

**[0049]** The user's ability to extract derivative data files is another function of the system software. The user has the ability to recall any target process previously saved data file, and identify a section of the data of real interest, and save that as a new derivative data file retaining the full functionality of any saved data file.

**[0050]** The system software also allows the user to select certain sensor inputs of special interest and view them in a separate window with an user-defined visual presentation, e.g., the user can choose the plot colors, the offsets, and the scales for the selected inputs. The user may also select to show or hide any input in the separate window.

**[0051]** Through the system software, the flexible process optimizer **100** can be configured to enable or disable inputs as desired from the available module circuits. The visual presentation of input data is customizable allowing the user to enter data identification labels and other pertinent information, including the user's notes and comments, for the various inputs. The user can enter the desired full-scale range for any sensor input within the sensor's capability. The customization and configuration

information is saved in the data file and can be edited as necessary.

[0052] The flexible process optimizer **100** has the ability to monitor vibration data simultaneously as it monitors process data. Vibration data is relatively fast compared to the main process data. The vibration data typically occurs at frequencies around a few kilohertz and is usually collected over a short time period often no more than a fraction of a second. By way of comparison, the process cycle in a typical discrete component production lasts several seconds or even minutes and, therefore, requires relatively slower data acquisition speeds. The system software recognizes the fact that the need to capture vibration in machine spindles, slides, and other components may change or may be of special interest during certain phases of a process cycle. Accordingly, the system software allows the user to capture vibration data either on demand or continuously along with the slow process data. The two data types are saved in separate data files or combined in a single data file at the user's discretion. The information about when the vibration data was acquired in a process cycle is also saved in the data file.

[0053] As previously discussed, the system software allows the flexible process optimizer **100** to be customized for most specific applications by facilitating the plotting of computed process parameters specific to a particular production process. The ability to plot multiple parameters is often needed for a thorough engineering analysis of the process and the production system capabilities and limitations and enables the user to readily visualize the effects of machine setup and process changes, which is vital for process improvement or optimization of any existing operation.

[0054] In the example of a production grinding system, the computed process parameters include cycle time analysis, cycle-to-cycle consistency, and wheel hungeriness. The cycle time analysis function performs a detailed breakdown of the times used on the individual components of a complete process cycle. A process cycle typically consists of various stages and components, which relate with the events taking place during these stages. Example may include a slide moving in rapidly to approach a part ready to be ground at the grinding cycle or the final disengagement of the grinding wheel from the ground work piece at the end of the cycle. Through the

cycle time analysis function, the operator can evaluate the overall production efficiency and determine the percentage of the total cycle time spent in each stage of the cycle. By comparing the cycle time analysis data from one operation with other similar operations, the user has the ability to evaluate and troubleshoot the production system. In addition, the user has a useful tool to evaluate the consistency of cycle times from piece to piece.

**[0055]** In addition to the consistency in the various cycle times, the system software provides a tool to check for variations in the behavior of the production system through the cycle-to-cycle consistency function. The behavioral variations include variations in stock on incoming parts, misfeeding of feed slides on the machine, improper settings on a size control gage, and changes in the ability of the wheel to remove material from a part. Such variations appear as distinct features or changes in the shapes of the data curves for different sensors during a process cycle. The cycle-to-cycle consistency analysis performs a quantitative analysis of a number of key parameters that are relevant to a particular process cycle. With respect to the example of the grinding system, the relevant parameters include: the spark-out time, the total cycle time, the spark-out power, the maximum grinding power, the total area under the curve, the apparent (total) stock removal, and the slope of the infeed curves.

**[0056]** The flexibility inherent in the flexible process optimizer **100** also allows the system software to compute and save special parameters that determine, and may limit, the system performance, that continuously change over time, and that may not be easy to control in real time. Returning to the example of the production grinding process, one such special parameter is the grinding wheel hungriness, which represents the ability of the grinding wheel to remove material from a workpiece. Grinding wheel hungriness continually changes based upon the length of service of the grinding wheel since installation of the wheel or dressing of the grinding and the relative hardnesses of the grinding wheel and the workpiece being ground.

**[0057]** The grinding wheel hungriness function derives present hungriness value of the grinding wheel from power consumption data obtained from a power sensor input and the feed rate data or the slide position slope data. Figure 17 illustrates a

typical graph of grinding wheel hungriness charting the material removal rate per unit width versus power per unit width for the cycle data of Figure 16. Points **P<sub>2</sub>**, **P<sub>3</sub>**, and **P<sub>4</sub>** represent the steady state power values during the feed rates **FR<sub>2</sub>**, **FR<sub>3</sub>**, and **FR<sub>4</sub>** in Figure 16 and **P<sub>0</sub>** is the idle power at the beginning and the end of the cycle. The plot is typically linear and the slope of this line, which represents the volumetric material removal rate per kilowatt of grinding power, is referred to as the grinding wheel hungriness (**H**). As the wheel engages in grinding each workpiece, it gradually dulls and the loss of sharpness is reflected in the computed hungriness parameter. Tracking the hungriness of the grinding wheel provides a user a quantitative criteria for determining key cycle setup parameters including how and when a wheel needs resharpening through dressing.

**[0058]** It should be emphasized that, although a production precision grinding system is used for illustrating this invention, the flexible process optimizer **100** is applicable to a vast majority of manufacturing operations in numerous industries. In addition to discrete component manufacturing like production grinding, other industries benefiting from the flexible process optimizer **100** of the present invention include paper and pulp manufacturing, food and pharmaceuticals processing, petrochemical processing, and many others. The user's ability to adapt the process optimization strategy based on visual display and some quantitative analysis of real time process sensor data that reflects the system behavior under the production conditions in use, permits optimization for both productivity and product quality in a balanced manner with instant feed back to confirm that the desired control is actually being achieved. The actual changes made to optimize the process can be made easily on the machine's CNC system settings or other manual adjustments normally possible on the machine.

**[0059]** From the foregoing description, it will be recognized by those skilled in the art that a device and method for monitoring a production machine that allows data display and analysis to develop and execute an immediate flexible process optimization methodology that is verifiable on the display of the flexible process optimizer. The flexible process optimizer allows the user to change the process control

strategy based on the observed actual behavior of the production system as revealed by sensors mounted on the machine for this purpose.

**[0060]** While the present invention has been illustrated by description of several embodiments and while the illustrative embodiments have been described in detail, it is not the intention of the applicant to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art. The invention in its broader aspects is therefore not limited to the specific details, representative apparatus and methods, and illustrative examples shown and described. Accordingly, departures may be made from such details without departing from the spirit or scope of applicant's general inventive concept.